

Jupiter's decisive role in the inner Solar System's early evolution

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The statistics of extrasolar planetary systems indicate that the default mode of planet formation generates planets with orbital periods shorter than 100 days and masses substantially exceeding that of the Earth. When viewed in this context, the Solar System is unusual. Here, we present simulations which show that a popular formation scenario for Jupiter and Saturn, in which Jupiter migrates inward from $a > 5$ astronomical units (AU) to $a \approx 1.5$ AU before reversing direction, can explain the low overall mass of the Solar System's terrestrial planets, as well as the absence of planets with $a < 0.4$ AU. Jupiter's inward migration entrained $s \gtrsim 10$ –100 km planetesimals into low-order mean motion resonances, shepherding and exciting their orbits. The resulting collisional cascade generated a planetesimal disk that, evolving under gas drag, would have driven any preexisting short-period planets into the Sun. In this scenario, the Solar System's terrestrial planets formed from gas-starved mass-depleted debris that remained after the primary period of dynamical evolution.

Solar System formation | planetary dynamics | extrasolar planets

A full understanding of the formation and the early evolution of the Solar System ranks among natural science's grand challenges, and, at present, even the dominant processes responsible for producing the observed planetary architecture remain elusive. Nonetheless, the past three decades have generated remarkable progress (1), and, critically, the discovery of thousands of extrasolar planets has placed Earth and the Solar System into the broader context of the galactic planetary census.

Perhaps the most important exoplanet-related discovery has been the realization that roughly half of the Sun-like stars in the solar neighborhood are accompanied by systems of one or more planets on low-eccentricity orbits with periods ranging from days to months, and masses falling in the $1M_{\oplus} < M_p < 50 M_{\oplus}$ range (2, 3), where M_{\oplus} is an Earth mass unit. This dominant population of planets (which often presents tightly packed, nearly coplanar multiple systems) contrasts sharply with the Solar System, whose inner edge is marked by Mercury's 88-d [0.4 astronomical units (AU)] orbit (see Fig. 1). An iconic example from the new planetary catalog is the Kepler-11 system, which encompasses at least six planets comprising more than ~ 40 Earth masses (4). In short, the exoplanetary surveys have revealed a hitherto unrecognized oddity of the Solar System. Relative to other Sun-like, planet-bearing stars, our terrestrial region is severely depleted in mass.

A few related peculiarities are also evident within the inner Solar System. Specifically, cosmochemical evidence suggests that while the fundamental planetary building blocks (planetesimals) formed within ~ 1 My of the Sun's birth (5), the final assembly of the terrestrial planets occurred on a timescale of 100–200 My, well after the dispersal of the nebular gas (6). This is at odds with the inferred compositions of extrasolar super-Earths, which are thought to have substantial gaseous atmospheres. Additionally, the exceptionally small masses of Mercury and Mars suggest that the terrestrial planets formed out of a narrow annulus of rocky debris, spanning 0.7–1 AU (where 1 AU is the mean distance between Earth and the Sun) (7). (See refs. 8 and 9 for an alternative view.) Such a narrow annulus is at odds with so-called minimum mass solar nebula (10, 11).

Within the framework of a radially confined solid component of the inner solar nebula, the inner edge of the annulus is entirely artificial. Indeed, at present, there exists no compelling justification for its origin. A plausible explanation may stem from the dynamical evacuation of solid material by a population of primordial close-in planets (12). We shall investigate this possibility further in this study.

Unlike the inner edge of the annulus, a body of previous work has demonstrated that the outer edge can be naturally sculpted by inward-then-outward migration of Jupiter (13). Within protoplanetary disks, long-range migration of giant planets results from tidal interactions with the nebula and viscous transport (14). For single planets, orbital evolution is typically inward. However, the process of resonant locking between two convergently migrating planets can lead to a reversal of the migration direction (15).

The process of resonant migration reversal for gap-opening planets (i.e., objects with $M \gtrsim M_{\text{Jup}}$) is a well-understood result of planet–disk interactions, and only requires the outer planet to be somewhat less massive than the inner. To this end, it is worth noting that all of the known mean motion commensurate pairs of giant planets that reside beyond $a \gtrsim 1$ AU have the more massive object on the inside (16, 17), suggesting that the operation of this mechanism is widespread. [A notable system within the resonant extrasolar population is GJ 876, where the inner planet is substantially less massive than the outer. In accordance with the picture of resonant transport delineated in ref. 18, this system likely failed to satisfy the conditions required for migration reversal and decayed to a compact orbital configuration (19).]

Within the Solar System, it is inferred that Jupiter initially migrated inward from its primordial formation site (presumably 3–10 AU) to ~ 1.5 AU, and subsequently reversed its evolutionary track as a consequence of locking into a 3:2 mean motion resonance with a newly formed Saturn. This special case of the generic resonant migration reversal mechanism is informally referred to as the “Grand Tack” scenario (13). In addition to the aforementioned truncation of the inner solid nebula, this putative sequence of events is attractive in that it naturally explains

Significance

The Solar System is an unusual member of the galactic planetary census in that it lacks planets that reside in close proximity to the Sun. In this work, we propose that the primordial nebula-driven process responsible for retention of Jupiter and Saturn at large orbital radii and sculpting Mars' low mass is also responsible for clearing out the Solar System's innermost region. Cumulatively, our results place the Solar System and the mechanisms that shaped its unique orbital architecture into a broader, extrasolar context.

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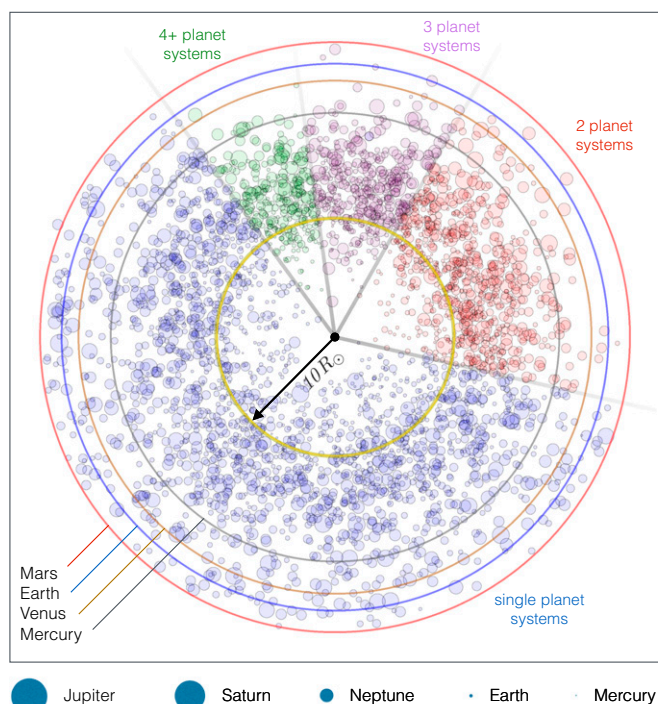


Fig. 1. Orbital distribution of sub-Jovian extrasolar planets. A collection of transiting planet candidates with radii $R < 5R_{\oplus}$ (where R_{\oplus} is an Earth radius unit), detected by the Kepler mission is shown. The radial distance away from the center of the figure represents a logarithmic measure of the planetary semimajor axis, such that the origin corresponds to the Sun's surface. The sizes of the individual points represent the physical radii of the planets. Further, the points are color-coded in accordance with multiplicity. The orbits of the terrestrial planets are also shown. Despite observational biases inherent to the observed distribution (e.g., transit probability, detectability) that work against detection of planets at increasing orbital radii, the raw contrast to our own Solar System is striking.

how the Solar System's giant planets avoided spiraling into the Sun (18), accounts for the origins of compositional differences within the Asteroid belt (13), provides a mechanism for delivery of water into the terrestrial region (20), and generates a compact orbital configuration needed for the subsequent instability-driven orbital evolution of the outer Solar System (21, 22).

Resonant Transport and Collisional Evolution

An early inward migration for Jupiter has a number of repercussions that come to light when one places the Solar System into the broader context provided by the observations of extrasolar planets. An inescapable consequence of Jupiter's trek is the resonant capture and the ensuing inward entrainment and transport of solid material (23). In particular, when a given planetesimal's orbital period becomes a nearly rational multiple of the orbital period of Jupiter, gravitational perturbations become coherent and force the planetesimal to maintain the same period ratio, leading to a decrease in the planetesimal orbit's semimajor axis (24). The most common commensurability at which capture occurs is 2:1, although numerous other possibilities exist.

In order for resonant interactions to be effective, the planetesimal in question must not be hydrodynamically coupled to the nebular gas on the orbital timescale. In practice, this means that the planetesimal size must significantly exceed $s \gg 1$ cm (25). Modern calculations of planetesimal formation suggest that planetesimals grow very rapidly to radii of order $s \approx 100$ km (26) and do not experience severe interactions with the nebula (27). Under such conditions, the entire solid component of the nebula

swept up by Jupiter's resonances will be captured and transported inward. In particular, if one adopts the conservative assumption of a minimum-mass solar nebula, and an oft-quoted solid-to-gas ratio of $\sim 1\%$, the total amount of mass swept up by the resonances is ~ 10 – 20 Earth masses, about an order of magnitude greater than the cumulative mass of the terrestrial planets.

A planetesimal that is driven inward by resonant migration experiences a concomitant increase in its orbital eccentricity. This effect is generally well understood and stems from adiabatic invariance (see [Supporting Information](#) for a discussion). The eccentricity of a planetesimal embedded in a gaseous nebula cannot grow indefinitely, however, as it is damped by aerodynamic drag. Thus, the adiabatic excitation of eccentricity typically stalls at a finite value dependent on the planetesimal size (which controls the magnitude of the dissipative forcing).

We have calculated the orbital evolution of $s = 10$ km, 100 km, and 1,000 km planetesimals as they are swept up by an inward-migrating Jupiter. The results of calculations corresponding to the nominal case of $s = 100$ km are presented in Fig. 2. (See [Supporting Information](#) for similar calculations corresponding to $s = 10$ km and 1,000 km planetesimals.) The simulations suggest

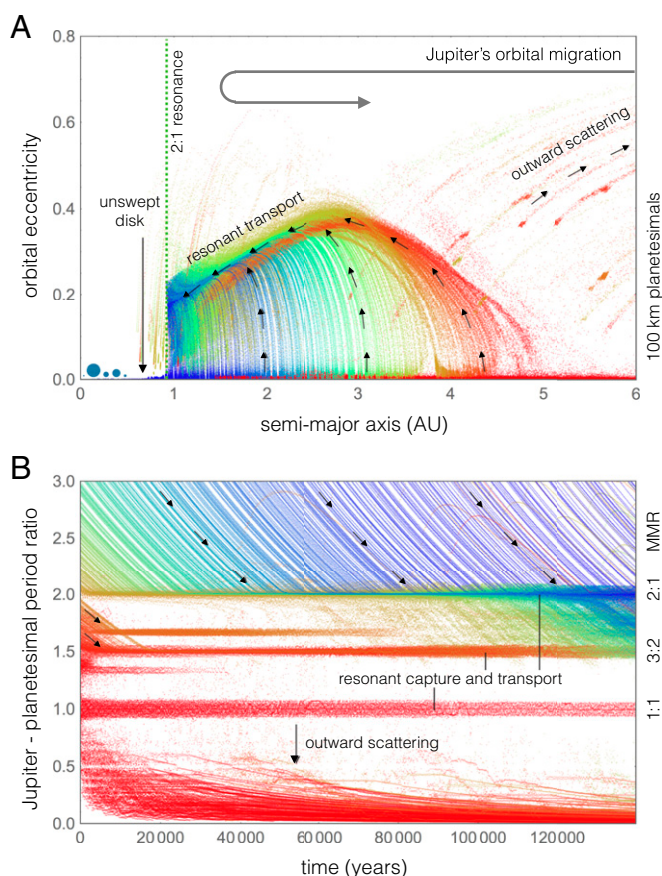


Fig. 2. Orbital evolution of planetesimals embedded in the solar nebula, under the effects of a migrating Jupiter. As Jupiter moves inward from 6 AU to 1.5 AU, planetesimals are swept up by mean motion resonances (MMRs). **A** shows the increase in the planetesimal eccentricity associated with resonant transport. Note that at the end of Jupiter's trek, there exists a strong enhancement in the planetesimal density at the Jovian 2:1 MMR. **B** depicts the preferential population of Jupiter's interior MMRs. Each planetesimal in the simulation is color-coded in accord with its initial condition, and the resultant curves track the orbital excursions of the small bodies as Jupiter's orbit shrinks. Jupiter's return to ~ 5 AU is not modeled directly. In the presented simulation, we assumed a planetesimal size of $s = 100$ km. Similar figures corresponding to $s = 10$ km and $s = 1,000$ km can be found in [Supporting Information](#).

that for the aforementioned planetesimal sizes, the equilibrium eccentricities are $e \approx 0.2, 0.3$, and 0.5 , respectively. Therefore, substantial orbital crossing will occur between planetesimals caught in resonances with Jupiter and those residing within as-yet-unswept regions of the disk.

The simulations reported in this work were terminated upon Jupiter's arrival at 1.5 AU. As already mentioned earlier, a resonant encounter with Saturn followed by reversal of migration is envisaged to have occurred subsequently. However, outward migration is not important to the problem at hand because interior material cannot be transported to wider orbits by this process.

Solid bodies on crossing orbits within densely populated disks experience collisions, which can result in either accretion or fragmentation. The outcome is principally determined by the specific energy of the impact: If this quantity exceeds a critical value characteristic of catastrophic disruption, the target is shattered into two or more pieces (28, 29). Adopting parameters appropriate for high-velocity impacts among strong basaltic objects in the gravity-dominated regime (see [Supporting Information](#) for these parameters), we find analytically that the specific impact energy safely exceeds its threshold value across the range of planetesimal sizes invoked above for impactor-to-target mass ratio of ~ 0.1 or greater (see [Supporting Information](#)). In other words, our results suggest that even though one may expect that the real planetesimal disk will harbor a distribution of planetesimal sizes, the trade-off between size-dependent orbital excitation and threshold impact energy leads to an environment where objects of any size above $s \gtrsim 10$ km can be destroyed by bodies that are ~ 10 times less massive. Jupiter's resonant shepherding of planetesimals thus initiates a collisional cascade (30) that grinds down the planetesimal population to smaller sizes.

Although the details of resonantly forced collisional grinding can be complex, an important feature of this process is that once the size of a given planetesimal population is diminished to a point where the effects of aerodynamic drag become important (for example, $s \lesssim 1$ km at 1 AU), the planetesimals will experience a runaway inward drift (27). Importantly, the same process facilitates the removal of material from Jovian resonances and thereby yields a critical planetesimal size below which collisional grinding subsides. Thus, the collisional cascade initiates well before Jupiter reaches its innermost tack, and proceeds as long as Jupiter's migration direction is inward.

Given the exceptionally large impact frequency expected within a mature protoplanetary disk and the dominantly destructive nature of collisions discussed above, we expect that a sizable fraction, if not all, of the transported population of planetesimals will be disrupted and undergo rapid orbital decay following Jupiter's reversal of migration direction. This feature is of critical importance for explaining the Solar System's lack of close-in super-Earths.

Decay of Primordial Close-In Planets

The dominant formation channel [distant formation followed by extensive inward migration (31) vs. in situ conglomeration (32, 33)] for extrasolar super-Earths remains controversial. However, a generally agreed-upon framework of core-nucleated accretion of giant planets dictates that the formation of solid multi-Earth-mass cores precedes the formation of giant planets (34). Thus, given that the formation of tightly packed close-in systems is ubiquitous in the galaxy, it can be reasonably speculated that at the time of Jupiter's inward journey, a similar population of first-generation planets existed in the Solar System. If such planets formed, however, they were destroyed.

In exactly the same way as an inward-migrating Jupiter captures planetesimals into resonance, inward-migrating planetesimals will lock into resonance with close-in planets. Provided that the cumulative mass of the resonant planetesimal population is not negligible compared with the mass of the close-in planets,

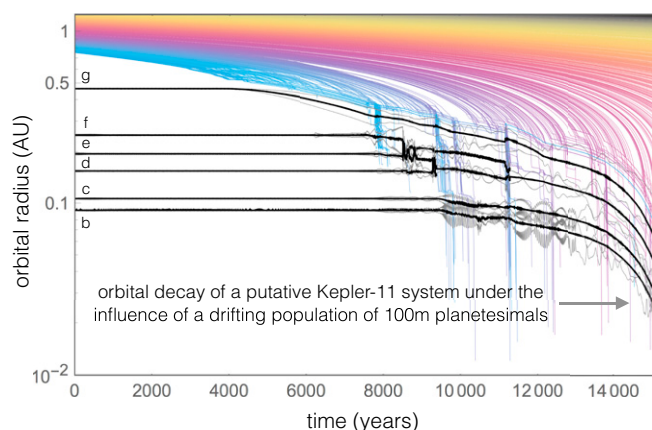


Fig. 3. Orbital decay of a hypothetical compact system of super-Earths (an analog of the Kepler-11 system) residing within the terrestrial region of the primordial Solar System. Following a collisional avalanche facilitated by Jupiter's migration, a population of planetesimals (here assumed to be ground down to $s=100$ m) decays inward and resonantly shepherds the interior planets into the star. Planetesimal orbits are shown with colored lines, while the planetary orbits are shown with black and gray lines. Specifically, the planetary semimajor axes are shown in black, while the perihelion and aphelion distances are shown in gray. Note that the results shown herein are largely independent of planetesimal size, as long as the planetesimals are small enough to drift inward on a timescale smaller than ~ 1 My due to aerodynamic drag.

the planetesimals will gravitationally shepherd the close-in planets into the Sun. In other words, the inward-then-outward migration of Jupiter in the early Solar System wiped the inner Solar System's slate clean, setting the stage for the formation of a mass-depleted, gas-starved second generation of terrestrial planets (1, 6). Indeed, within the framework of this picture, the material from which Earth formed is either the remainder of the violent collisional avalanche or has been largely emplaced by Jupiter's outward migration.

To illustrate the above process, we examined the dynamical evolution of the Kepler-11 planetary system when placed within the inner edge of the solar nebula, and under the gravitational influence of an extensive population of exterior, inward-drifting planetesimals. (This example is used for definitiveness. We are not suggesting that a primordial population of the Solar System's close-in planets would have necessarily borne any similarity to the Kepler-11 system.) The computed evolutionary sequence is shown in Fig. 3. Clearly, dissipative resonant transport provides an efficient mechanism for driving close-in planets into the central star. Indeed, the sequence of events associated with Jupiter's so-called Grand Tack may well have constituted a veritable grand attack on the Solar System's original population of short-period super-Earths.

Discussion

This scenario provides a natural explanation for why the inner Solar System bears scant resemblance to the ubiquitous multi-planet systems discovered by the Doppler velocity surveys and by the Kepler mission. Moreover, the physical processes that we invoke (namely, giant planet migration, collisional disruption of planetesimals, aerodynamic drag, and resonant shepherding) are generic. In consequence, the mechanism described herein should also operate within a nonnegligible fraction of extrasolar planetary systems. Accordingly, a series of observational predictions can be formulated.

First, our calculations imply a strong anticorrelation between the existence of multiple close-in planets and giant planets at orbital periods exceeding ~ 100 days within the same system. The

existing exoplanet catalog is not yet sufficiently detailed to test this hypothesis (17). However, direct assessment of the validity of this prediction will be provided by the upcoming TESS and K2 missions. Second, the spectral energy distributions of protoplanetary disks hosting gap-opening planets should exhibit strong infrared enhancements (35), as a consequence of collisional heating and the associated production of dust. Moreover, dust emission

morphologies in such disks could, in principle, exhibit asymmetrical structure (36). Most dramatically, our work implies that the majority of Earth-mass planets are strongly enriched in volatile elements and are uninhabitable.

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